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Retrieval of black carbon absorption from proposed satellite measurements over the ocean glint

Y. J. Kaufman[1], J. V. Martins[2], L. A. Remer[1] M. R. Schoeberl[1] and M. A. Yamasoe[3]

Popular Summary
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Haze and air pollution includes many chemicals that together form small particles suspended in the air called aerosols. One of the main ingredients found to affect climate and human health is Black Carbon. Black particles emitted from engines that do not burn the fuel completely, e.g. old trucks. Black carbon absorption of sunlight emerges as one of the key components of man-made forcing of climate. However, global characterization of black carbon emissions, distribution and pathways in which it can affect the amount of solar radiation absorbed by the atmosphere is very uncertain. A new method is proposed to measure sunlight absorption by fine aerosol particles containing black carbon over the ocean glint from a satellite mission designed for this purpose. The satellite will scan the same spot over the ocean in the glint plane and a plane 40° off-glint a minute apart, collecting measurements of the reflected light across the solar spectrum. First the dark ocean off the glint is used to derive aerosol properties. Then the black carbon absorption is derived from the attenuation of the bright glint by the aerosol layer. Such measurements if realized in a proposed future mission – COBRA are expected to produce global monthly climatology of black carbon absorption with high accuracy (±10 to 15%) that can show their effect on climate.

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Retrieval of black carbon absorption from proposed satellite measurements over the ocean glint

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Abstract: Black carbon absorption of sunlight emerges as one of the key components of man-made forcing of climate. However, global characterization of black carbon emissions, distribution and pathways in which it can affect the energy balance is very uncertain. A new method is proposed to measure sunlight absorption by fine aerosol particles containing black carbon over the ocean glint from a satellite mission designed for this purpose. The satellite will scan the same spot over the ocean in the glint plane and a plane 40° off-glint a minute apart, collecting measurements of the spectral polarized light across the solar spectrum. First the dark ocean off the glint is used to derive aerosol scattering properties. Then aerosol absorption is derived from the spectral reflectance of the bright glint observed through the aerosol layer. For aerosol optical thickness of 0.2 to 0.4 the method should be able to map global distribution of black carbon absorption over oceans and inland waters with an error of ±25% over a period of 4 days. Such measurements if realized are expected to produce global monthly climatology of black carbon absorption with high accuracy (±10 to 15%) or an error in the single scattering albedo of ±0.01.

1. Introduction

Large concentrations of black carbon (BC) were measured in regions with intense biomass burning in Africa [Eck et al 2001] and South America [*Kaufman et al.* 1998] and pollution over the Indian ocean [*Ramanathan et al* 2001]. Over this large polluted regions BC was shown to absorb on average 7% of sunlight reaching the surface, or 17 W/m^2. Over a large Atlantic Ocean region smoke from African biomass burning absorbs 20 W/m^2 [*Kaufman et al.*, 2001b]. The global average BC absorption of solar radiation is estimated to be 0.5 W/m^2, a third of CO_2 radiative forcing [*Haywood and Boucher*, 2000]. It is amplified by the "semi-direct" effect, in which cloud fraction is reduced by the effect of BC warming on the temperature and humidity profiles [*Hansen et al.*, 1997; Ackerman et al., 2000]. BC in smoke can reduce the reflectivity of developed clouds by 10% [*Kaufman and Nakajima*, 1993], reducing reflection to space and enhancing warming. These effects on clouds can increase BC forcing significantly. Reacting to these findings, Andreae [2001] suggested that: "if research investment were to be scaled by climate impact, these figures would suggest that resources at the level of about one-third of those now devoted to carbon-cycle research should go into BC studies".

Current estimates of BC concentration and absorption are uncertain due to uncertainties in the in source estimates (factor, x2), life-time in the atmosphere (x2) and BC light absorption efficiency (x2) [*Tegen et al.*, 2000; *Martins et al.*, 1998]. Future trends of BC are unknown, though in the last 40 years its industrial/urban sources have tripled [*Tegen et al.*, 2000]. Similar increases may be expected in the next decades due to the expansion of economic activity in East and South Asia, with possible large unsustainable effects on global climate. Since reduction of emission of aerosol rich with black carbon may be independent of restrictions on energy use, it has the potential to provide an additional tool to reduce global warming. If proven against measurements, the difference between uncontrolled and controlled emissions of aerosol rich with BC can reduce the anticipated radiative forcing in the next 50 years by ~1 Wm^{-2} [*Hansen et al.*, 2000].

Spaceborne instruments are needed to measure the global distribution and evolution of BC absorption due to the heterogeneity of sources and concentration. Satellites were used to measure aerosol absorption over bright land, but only in specific conditions [*Kaufman et al.*, 2001a]. Here we suggest a new method that uses measurements of the spectral attenuation of glint reflectance by aerosol to derive continuously the distribution of fine mode aerosol containing absorbing BC over the oceans (Fig. 1). The CO2, Black Carbon Radiation and Aerosol (COBRA) satellite mission proposed for this purpose measures also CO2 absorption over the glint to derive variability in its concentration. The method resembles water vapor measurements using glint absorption [*Kleidman et al.*, 2000]. COBRA is the only proposed satellite mission combining wide spectral range and polarization, specially designed for aerosol retrievals.

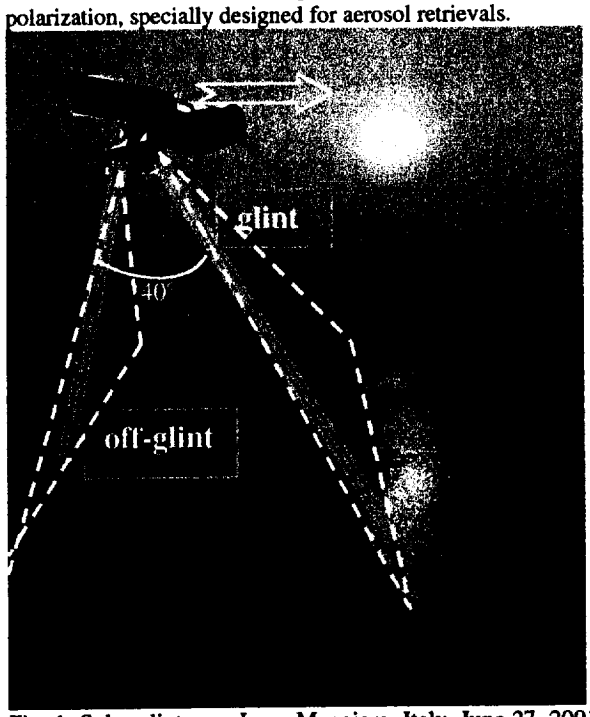

Fig. 1: Solar glint over Lago Maggiore, Italy, June 27, 2001. The haze is a regional, heavy pollution (optical thickness~1) and dust transported from the Sahara [*Gobbi et al.*, 2000]. Dust preferential absorption in the blue part of the spectrum gives the glint its golden color. The COBRA measurement planes through the glint and off-glint, 40° apart, are shown. The arrow shows the direction of the spacecraft movement.

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2. Use of ocean glint to measure absorption

The solar glint is a specular reflection of sunlight by the water surface. The glint use to measure absorption is a type of solar occultation measurement but has some advantages over standard solar occultation (e.g. Stratospheric Gas and Aerosol Experiment, SAGE-II) in that there is much less interference by clouds. The usual disadvantage of the glint is that the brightness and width of the glint depends on the slope distribution of surface capillary waves, which are determined by unknown winds. The algorithm discussed here is developed to minimize sensitivity to this problem. Figure 2 shows a simulation of the aerosol effect on observations of the glint from space for a typical wind speed of 6 m/s. Outside the glint aerosol increases the ocean brightness observed at the top of the atmosphere (positive values in Fig. 2). In the glint region, aerosol reduces the glint brightness both through absorption and scattering. Aerosol absorption is twice as effective as scattering in darkening the glint, since it removes the photons from the beam rather than scattering them to a different direction, that may not be outside the glint. A moderate uncertainty in aerosol scattering properties derived from the off-glint observations (e.g. in the effective radius r_{eff} of Δr_{eff} = 0.05 μm and in the refractive index n_r by Δn_r =0.05) affects the ocean brightness outside the glint as much as a change in the aerosol absorption optical thickness τ_{abs} of $\Delta \tau_{abs}$ =0.03 (see Fig 2). However, inside the glint these uncertainties have a negligible effect, probably due to compensation between changes in attenuation of the glint brightness by changes in the aerosol forward phase function and changes in the increase in the overall image brightness due to changes in the backscattering phase function. These two effects tend to cancel each other for a glint shape associated with wind speed of ~6 m/s. This resilience against uncertainties in the aerosol scattering properties improves derivation of the aerosol absorption over the glint. Note that for low wind speed (< 3 m/s) the glint is narrow and therefore will be sensitive to the aerosol scattering properties. For strong winds (> 10 m/s) the glint is not bright enough to be sufficiently sensitive to aerosol absorption. This method is similar to remote sensing of aerosol absorption over the land [*Fraser and Kaufman*, 1985; *Kaufman* 1987; *Kaufman et al.*, 2001a]. The land method is based on simultaneous observations of nearby bright and dark surfaces through the aerosol. The dark surface is used to derive the aerosol scattering properties and then the bright surface to derive absorption. Over the ocean simultaneous observations of the same region of the ocean at glint and off glint directions are required to apply a similar approach.

3. The remote sensing method

COBRA has two spectral polarimeters (EOSP - Mishchenko and Travis [1997]). Both EOSP instruments scan across the satellite track. One points always to the center of the glint and scans through it, the second scans at 40° from the glint to see the same spot a minute apart at an off-glint direction (see Fig. 1). The following algorithm describes the method to derive first the aerosol scattering properties from the COBRA observations outside the glint followed by derivation of the aerosol absorption from the glint spectral measurements:

1) In the off-glint direction, remote sensing of the dark ocean in a wide spectral range (0.34-2.1 μm) with polarization is used to derive the aerosol scattering optical thickness, size distribution and refractive index. In the glint direction the EOSP scan is much wider than the glint, offering a second view direction of the dark ocean (off-glint) through practically the same atmosphere.
2) Glint spectral measurements at 1.6 and 2.1 μm are used to derive the glint reflectance in a spectral region where fine mode aerosols are transparent (See Fig. 3). A model relates the glint brightness in 1.6 or 2.1 μm to the 0.44-0.86 μm range. Thus we can remove the effect of the variation in glint brightness with sea surface state.
3) The aerosol attenuation of the glint in the 0.44-0.86 μm range is derived from the difference between the measured reflectance and the glint reflectance. Using the aerosol scattering properties derived from off-glint, the attenuation in the 0.44-0.86 μm range is translated into spectral solar absorption.
4) Using the 2 UV channel polarized light and the derived particle size distribution, COBRA derives the aerosol scattering and absorption optical thickness in the UV [*Torres et al.*, 1998] and the aerosol average elevation.

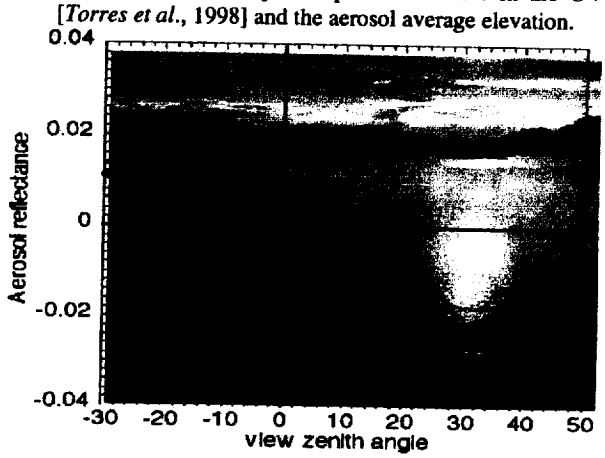

Fig. 2: Solar glint in Lago Maggiore, Italy on a pristine day (June 14, 2001 – aerosol optical thickness τ_a=0.02) overlaid by a plot of the aerosol reflectance at 0.55 μm as a function of the view zenith angle. Aerosol reflectance is the difference between the reflectance at the top of atmosphere for a given τ_a and for τ_a=0. Solar zenith angle is 30°. Green line – base model: τ_a=0.2, refractive index n_r=1.40, single scattering albedo ω_o=0.96, effective radius r_{eff}=0.15 μm. Black line, n_r=1.45. Blue line, r_{eff}=0.20 μm. Red line, ω_o=0.80. The aerosol reflectance in the glint is robust against changes in most aerosol properties but sensitive to its absorption.

Figures 3 demonstrates the method to derive aerosol absorption from glint observations for 3 types of aerosol with different single scattering albedo. Aerosol decreases the glint reflectance as measured from space mainly in the 0.44 to 0.86 μm range. The change in the measured reflectance, termed the aerosol reflectance, differs among the 3 aerosol types due to differences in the BC concentration and corresponding single scattering albedo, size distributions, and refractive indices. The higher the optical thickness, or the lower the single scattering albedo, the larger is the aerosol effect on reduction of the glint reflectance. At 1.65 to 2.1 μm the aerosol effect on the glint reflectance is small. The residual effect is due to absorption and scattering by the coarse mode. Presently we can only guess the single scattering albedo at the long wavelengths, shown in the figure. However we do not expect large deviations from this figure for aerosol with dominant fine mode since the optical thickness decreases quickly with wavelength (see Fig 3). Since we do not know the actual glint reflectance, aerosol absorption is derived from the difference in the aerosol reflectance in wavelength range where it is significant -

$0.44<\lambda<0.66$ μm and at wavelengths where it is very small $\lambda \geq 1.6$ μm. Aerosol reflectance at 0.44-0.86 μm range is ~10 times larger in magnitude than at 2.1 μm. Therefore aerosol absorption is derived from the absorption function A:

$$A(\tau_a,\omega_0,\lambda)=[\rho^*(\tau_a,\omega_0,\lambda)-\rho^*(0,,\lambda)]-[\rho^*(\tau_a,\omega_0,2.1)-\rho^*(0,,2.1)]$$

where $\rho^*(\tau_a,\omega_0,\lambda)$ is the spectral reflectance of the glint as observed from space for wavelength λ and optical thickness τ_a. $\rho^*(0,,\lambda)$ is the value with no aerosol. A lookup table of A for variety of aerosol scattering properties, optical thickness and values of the spectral single scattering albedo is used to derive the aerosol absorption. An assumed relationship between the aerosol absorption at 2.1 μm and that at the shorter wavelengths is used. It is presently based on aerosol climatology [*Dubovik et al.*, 2001], but will have to be refined with actual aerosol absorption measurements for 1.65 and 2.1 μm channels, presently not available from AERONET. An example of the relationship between the absorption function A and the aerosol single scattering albedo is given in Fig. 4 for fine aerosol particles. Sensitivity to the assumed ω_0 at 2.1 μm and to the aerosol size and refractive index is also shown.

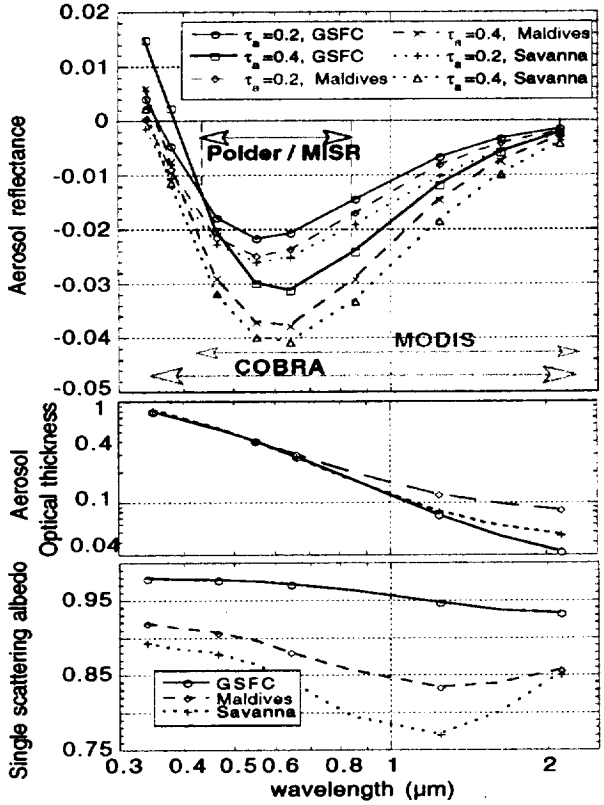

Fig. 3: Aerosol reflectance over the glint for wind speed of 7 m/s, defined as the difference between top of atmosphere reflectance with and without aerosol. Blue, red and black lines - three aerosol types: regional US pollution in GSFC-Maryland, South-East Asia pollution in Maldives Island during the INDOEX experiment, and Savanna burning in Africa during the SAFARI-2000 experiment, respectively. The spectral optical thickness and the single scattering albedo for each aerosol type are plotted in the lower figures. The aerosol model is after Dubovik et al. [2001]. The optical thicknesses is given for λ=0.55μm. Note that the optical thickness decreases by factor of 5, 8 and 10, from 0.55 μm to 2.1 μm for Maldives, Savanna and GSFC respectively. The spectral range of COBRA is compared with that of MISR, POLDER and MODIS (horizontal arrows).

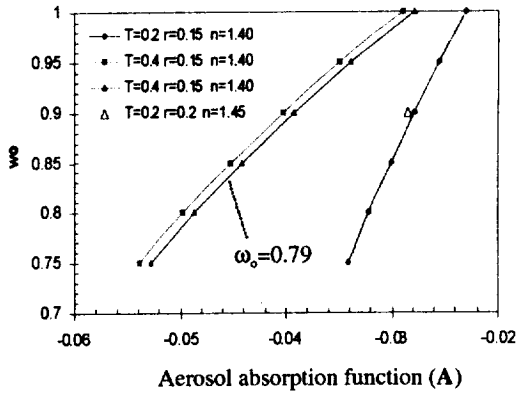

Fig. 4: Single scattering albedo at 0.55 μm as a function of the absorption function A for fine mode aerosols with optical thickness of 0.2 and 0.4, effective radius of R_{eff}=0.15 μm, real refractive index of n_r=1.40 and single scattering albedo, ω_0, at 2.1 μm of ω_0=1.0. The sensitivity to R_{eff}=0.2, n_r=1.45 and to ω_0 at 2.1 μm of 0.79, is shown. Single scattering albedo has a strong dependence on the absorption function A but also to other aerosol properties. An accurate determination of optical depth, effective radius, and refractive index with the off-glint geometry and polarization can narrow down the uncertainties in the absorption measurement.

4. Sensitivity study

The sensitivity of the derived aerosol absorption from measurements in the center of the glint to calibration errors, errors in the effective radius, refractive index and optical thickness is tested and summarized in Table 1. The errors are based on analysis of Mishchenko and Travis [1997] though for a different spectral and angular range. The monthly errors are calculated assuming that errors in the aerosol properties are half random and that half of the calibration uncertainty will be reduced using validation in pristine oceanic sites with little absorption. Thus half the individual errors are used in the monthly RMS. In the short wavelengths of 0.34-0.55 μm the monthly RMS error for these assumptions is ~13% for optical thickness of 0.2 and ~9% for 0.4.

The spectral analysis of Table 1 is for the center of the glint. The angular dependence of the sensitivity of detecting aerosol absorption is shown in Fig. 5 for wavelength of 0.55 μm. The ratio of signal due to aerosol absorption to RMS errors due to uncertainty in aerosol properties is larger than 4 over a swath of 550 km. The absorption signal shown in the figure is due to a typical change in the single scattering albedo of 0.1. The COBRA mission is in polar orbit therefore the 550 km wide area gives a global coverage in 4 days. The calculations are for solar zenith angle of θ_o=30°. Similar results are obtained for θ_o<30°. For θ_o~60° the glint region is significantly narrower. Therefore, the best analysis of aerosol absorption can be obtained for θ_o< 45° corresponding to a 90° latitude wide band varying seasonally with the solar position. The calibration accuracy used in Table 1 can be achieved by continuous intercomparison with AERONET measurements of aerosol absorption over clean oceanic sites (absorption of $\Delta\tau_{abs}$~0.004 and similar uncertainty) [Smirnov et al 2001]. Climatology of the aerosol optical thickness on a monthly 1° latitude x 1° longitude can decrease the error, resulting in uncertainty of $\Delta\tau_{abs}$~0.002 ($\Delta\omega_0$~0.01) or 10%.

Table 1: Sensitivity of derivation of aerosol absorption optical thickness, τ_{abs} to errors, for single measurements: calibration error, ε_c, of 3% for $\lambda < 2.1$ μm, and 1% at 2.1 μm, error in effective radius $\varepsilon_{R\text{-}eff}$ of ΔR_{eff}=0.05 μm, in aerosol optical thickness, ε_τ, of $\Delta\tau/\tau$= 0.05, in real refractive index, ε_n, of Δn_r=0.03, and in the aerosol height, ε_H, of ΔH=1 km. The RMS errors are also computed. For the monthly values half of the errors are assumed.

λ μm	τ_{abs}	ε_C from 3% to 1%	$\varepsilon_{R\text{-}eff}$ ΔR_{eff} =0.05 μm	ε_τ $\Delta\tau/\tau$= 0.05	ε_n Δn_r= 0.03	ε_H ΔH= 2 km	RMS single Case	RMS monthly
Aerosol optical thickness of 0.2 (0.55 μm)								
0.34	**0.032**	**20**	**-15**	**2**	**8**	**-17**	**27**	**14**
0.38	**0.028**	**15**	**-3**	**2**	**11**	**-12**	**19**	**9**
0.47	**0.025**	**14**	**13**	**-5**	**14**	**-5**	**23**	**11**
0.55	**0.021**	**23**	**3**	**-23**	**12**	**-2**	**34**	**17**
0.64	0.017	37	-37	-52	8	2	74	33
0.86	0.012	85	>100	>100	-9	4	-	-
Aerosol optical thickness of 0.4 (0.55 μm)								
0.34	**0.064**	**10**	**-22**	**0**	**5**	**-14**	**28**	**13**
0.38	**0.056**	**7**	**-19**	**2**	**7**	**-9**	**23**	**11**
0.47	**0.049**	**8**	**-11**	**0**	**10**	**-4**	**16**	**8**
0.55	**0.042**	**12**	**-15**	**-8**	**11**	**-1**	**23**	**11**
0.64	0.034	20	-37	-25	11	1	50	25
0.86	0.023	42	>100	-86	-2	4	-	-

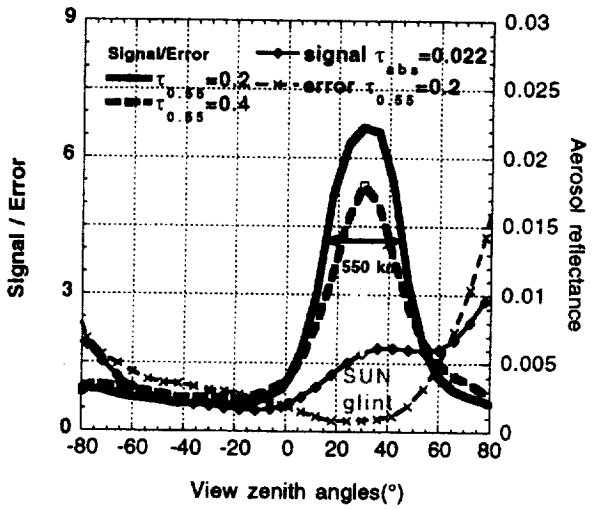

Fig. 5: Signal and error for detecting an increase in aerosol absorption of $\Delta\tau_{abs}$=0.022 for optical thickness of τ=0.2 at 0.55 μm, and signal/error ratio for $\tau_{0.55}$=0.2 and 0.4. The signal is the effect of absorption on aerosol reflectance. The error is RMS of uncertainty in the optical thickness, particle size, refractive index and aerosol height (see Table 1). Signal/error is larger than 3 and 4 respectively for τ=0.2 and 0.4 across a swath of 550 km.

5. Conclusions

A new spaceborne observation strategy of absorption by fine aerosol black carbon is proposed in the COBRA space mission. It offers the possibility to observe fine aerosol absorption of sunlight over oceans and inland waters with errors of ±25% for individual observations and ±10% monthly average. This is achieved for a 550 km wide swath of the solar glint, thus offering a global coverage in 4 days. This accuracy is calculated for moderate wind speeds (~6m/s) and for low solar zenith angles (e.g. < 45°). The method is not as good for high (≥10m/s) or low (≤3m/s) wind speeds. The method offers to generate a climatology of black carbon absorption with high accuracy corresponding to error in the single scattering albedo of ±0.01. The method was developed for aerosol dominated by fine particles (R_{eff}<0.5 μm). The effect of significant coarse mode needs to be determined, however its properties at 2.1 μm need to be measured first. The method of observation is new, very promising, but awaits scrutinity against measurements to test if these high accuracies can be supported.

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